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Tomographic images of a mantle circulation model

Hans-Peter Bunge

Department of Geosciences, Princeton University

J. Huw Davies

Department of Earth Sciences, University of Liverpool

Abstract. Sampling convection in the Earth's mantle by seismic tomography is difficult as evidenced by the uneven distribution of seismic stations and events with some regions being well imaged compared to others. Here we quantitatively explore tomographic filtering on Earth structure by tracing ISC P-body-wave data through a computer simulation of mantle circulation which accounts for internal heating of the mantle by radioactive decay, heatflux from the core, a depthwise increase in viscosity, and plate motion history of the past 120 million years. The travel time residuals are inverted by solving jointly for structure and hypocentral parameters with explicit damping and smoothing. We recover the Farallon and Tethys slabs as well as some low velocity anomalies associated with hot upwelling flow suggesting that tomographic filtering is probably minor in areas of high ray density.

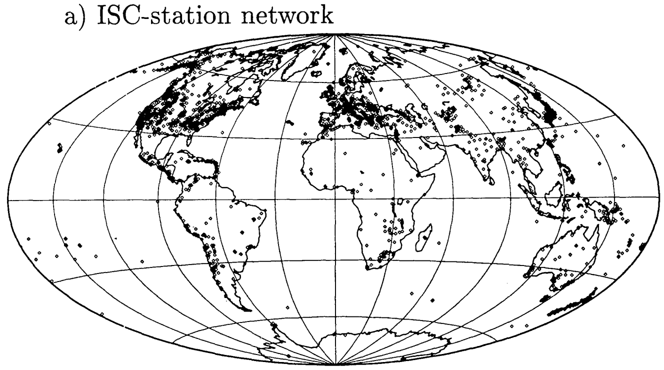
1. Introduction

Mantle convection is driven by lateral density variations arising in large part from the subduction of ancient oceanic lithosphere. Two widely recognized approaches constrain these density variations. First, they are inferred from seismic tomography which now provides detailed images of mantle heterogeneity [*Grand et al.*, 1997; *van der Hilst et al.*, 1997]. The second approach uses mantle circulation models (MCMs) incorporating the history of Mesozoic and Cenozoic plate motion. The large-scale mantle structure is directly related to the history of subduction [*Richards & Engebretson*, 1992]. Thus MCMs are a powerful tool to study the evolution of mantle heterogeneity.

Comparing seismic and geodynamic mantle models is a fundamental problem owing to their vastly different resolving power. MCM resolution is controlled by computational advances, and high resolution circulation studies are now feasible on modern parallel computers [*Bunge et al.*, 1998]. The accuracy of tomographic models is controlled mainly by mislocation of seismic events, data errors, the uneven distribution of seismic sources and receivers, and the linearization commonly adopted in tomographic inversions. Together these limitations impose a complex spatial filter which must be considered by geodynamicists who compare MCMs to seismic studies of the mantle.

Seismic filtering has been explored by *Johnson et al.* [1993] and *Megnin et al.* [1997] in mantle convection models. However, MCM heterogeneity is more complex and directly related to the spatial distribution of seismic sources and receivers. Here we focus on the effect of incomplete ray coverage using short-period International Seismological Centre (ISC) P-body-wave data. We demonstrate that the tomographic filter in this case is dominated by the density of seismic ray-sampling, which is high in the northern hemisphere and probably sufficient to resolve heterogeneity associated with circulation modeling.

a) ISC-station network



b) Event distribution used for this study

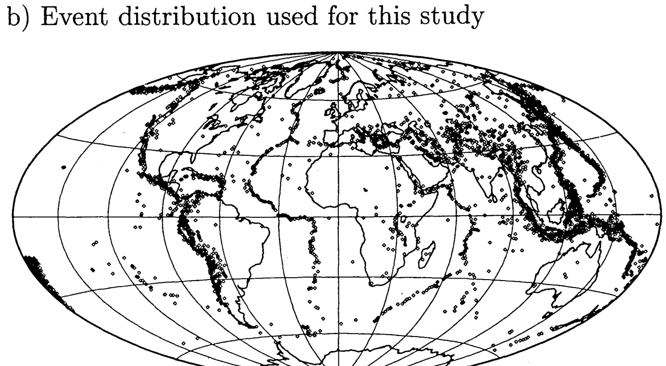


Figure 1. a) Network of ISC stations. Station density is high in the northern hemisphere and over continents. b) Location of seismic events used for this study.

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2. The tomographic filter

All seismic imaging studies of the mantle are restricted by the inhomogeneous distribution of seismic stations and events. We illustrate this spatial limitation for P-body-wave teleseismic ISC data. This data is also a large component of the data-sets of *van der Hilst et al.* [1997] and *Vasco et al.* [1995]. Figure 1a shows that the station density is high only in North America, Europe and Japan. Global seismicity is also inhomogeneous being concentrated along plate-boundaries especially in the subduction zones of the Pacific as illustrated in Figure 1b. Consequently it is difficult to obtain a dense ray sampling for some regions, in particular beneath the Pacific and in the southern hemisphere. For this study we use the reprocessed ISC data-set of *Engdahl et al.* [1998]. We parameterize the mantle with 29 radial layers, each 100 km thick and including 44,000 square equal area cells (one degree by one degree at the equator). To reduce the large event redundancy inherent in the ISC catalogue we select only one event per cell having the best azimuthal and epicentral distribution of phases, and we account only for events with at least one hundred reported phases. Even with this subselection we retain more than 780,000 phases corresponding to 3800 events (Figure 1b).

The uneven sampling of the data-set is evident in Figure 2, where we show the tomographic ray density at 6 depth levels. Ray sampling in the upper mantle is highest under Europe, Japan, North America and the tectonically active regions. Ray sampling in the lower

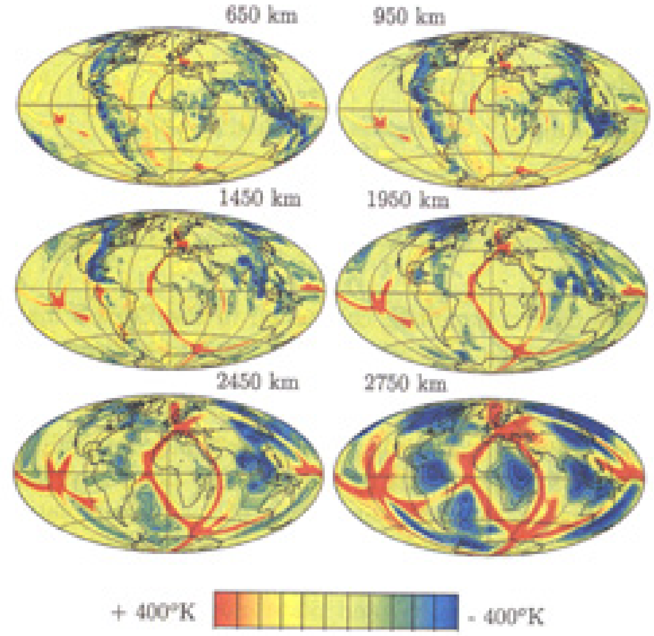

Figure 3. De-meaned MCM heterogeneity at six depth levels. Blue is cold and red is hot. Cold mantle persists in places of past subduction. Hot upwellings are located in the Mid-Atlantic and under the Pacific.

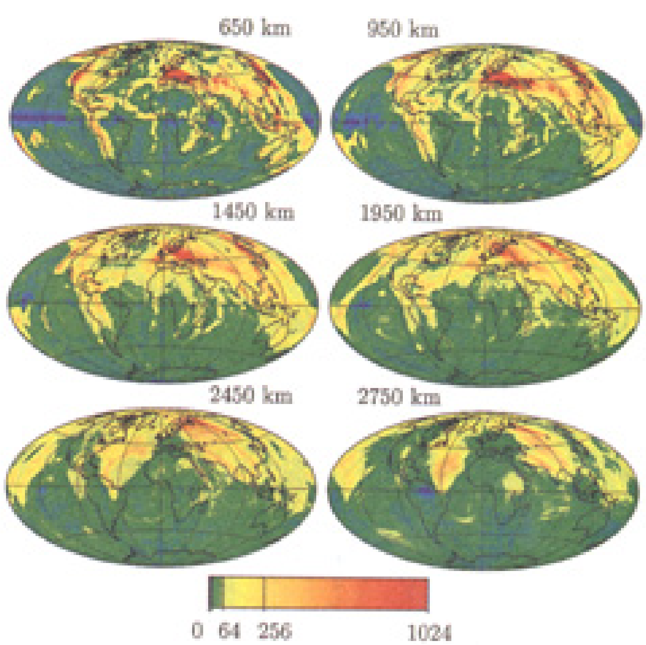

Figure 2. Ray density per tomographic cell at six depth levels on a logarithmic scale. Blue is low, and red is high. Rays are concentrated under continents in the northern hemisphere.

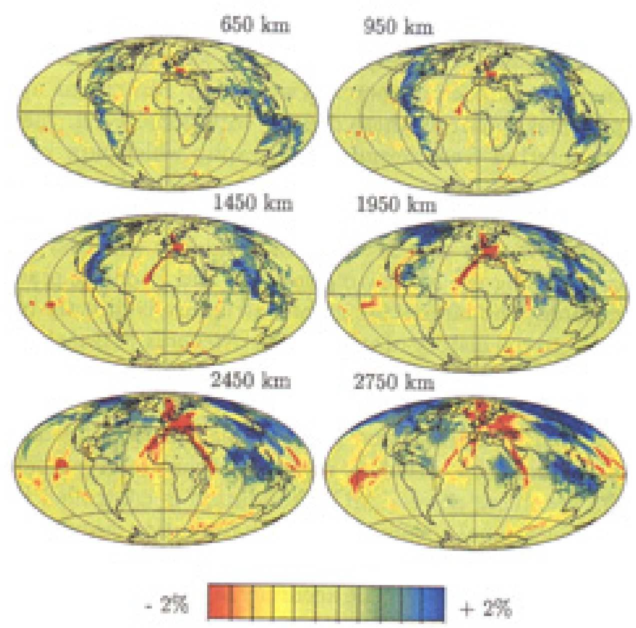

Figure 4. De-meaned MCM P-velocity heterogeneity after inversion. Blue is fast and red is slow. Recovery of MCM heterogeneity is generally good for regions of high density in the northern hemisphere and under continents, but poor in the southern hemisphere and near the CMB.

mantle is more even, but average sampling per cell is smaller. Near the Core Mantle Boundary (CMB) maxima of ray sampling exist beneath the North Atlantic, the North Pacific and Mid-Asia, but the southern hemisphere is poorly sampled at all depth levels.

3. Input MCM and seismic inversion

The input MCM is shown Figure 3. Mantle flow is calculated using the TERRA code [*Bunge & Baumgardner*, 1995] and imposing the history of Cenozoic and Mesozoic plate motion [*Lithgow-Bertelloni & Richards*, 1998]. We assume the viscosity in the lower mantle and in the lithosphere increases by a factor of 100 relative to the upper mantle value (8.0×10^{21} Pa s), as suggested by studies of the geoid [*Hager & Richards*, 1989]. We also assume the mantle is isochemical and heated primarily from within, with an additional 25 percent core heating [*Davies*, 1988]. Our modeling assumptions correspond to simple whole mantle flow [*Davies & Richards*, 1992], and the main physical effects are fairly well understood from previous mantle convection studies [*Tackley et al.*, 1993; *Bunge et al.*, 1996].

MCM heterogeneity at all six depth levels is dominated by linear cold downwellings at places of past subduction. Relatively hot mantle is concentrated beneath the Mid-Atlantic and the South Pacific corresponding to upwellings away from subduction zones. Near the CMB heterogeneity is dominated by large-scale structure as the cold downwellings spread laterally. A complementary pattern of warm structures is also developed where subduction has not occurred. These characteristics have been described in detail elsewhere [*Bunge et al.*, 1998], and are in remarkable agreement with tomographic mantle images [*Grand et al.*, 1997; *van der Hilst et al.*, 1997].

We compute seismic travel times by converting the demeaned MCM temperatures into a 3-D seismic slowness (1 / velocity) model, i.e. we convert lateral temperature anomalies into lateral seismic anomalies. Note that we implicitly assume that the underlying 1-D seismic reference profile is perfect. For simplicity we adopt a constant temperature to seismic velocity conversion factor of $2 \times 10^{-6} s/km/K$, in line with the available experimental data for silicates in the lower mantle [*Duffy & Ahrens*, 1992]. We trace some 780,000 rays through our model, using IASP91 [*Kennett*, 1991] as the 1-D reference velocity model. Travel time residuals are evaluated by integrating slowness perturbations along each ray path, where residuals are defined as the 'observed' minus the 'predicted' travel time. Note that 'observed' travel times correspond to the MCM, while 'predicted' travel times correspond to IASP91. The residuals are inverted following the method of *Rhodes & Davies* [1997], which jointly solves for structure and hypocentral parameters [*Spakman*, 1988; *Pulliam et al.*, 1993] with explicit damping and smoothing [*van der Hilst et al.*, 1997; *Pulliam et al.*, 1993]. The inversion uses 50 iterations of a SIRT algorithm and leaves the source depth fixed, because no depth phases were included.

4. Results

Heterogeneity of the input MCM may be compared to the MCM after inversion (Figure 4). Looking first at the northern hemisphere, we recover the prominent Farallon and Tethys slabs located in the upper 1000 km of the lower mantle beneath America and Eurasia. Below 1500 km depth, the inverted model is increasingly dominated by low velocity anomalies centered under Europe and the Mid-Atlantic and corresponding to hot upwelling flow in the input MCM. Near the CMB the inversion captures the long-wavelength heterogeneity of the input MCM. In contrast, MCM heterogeneity in the southern hemisphere is poorly reproduced. We therefore suggest that seismic filtering effects on geodynamic structure are probably minor, especially for anomalies related to past subduction. Thus a significant part of mantle heterogeneity expected from geodynamic modeling is probably well imaged by tomography.

We must qualify our conclusions by noting that we singled out uneven ray coverage in the tomographic filter, effectively ignoring errors arising from source mislocation, errors in the data, imperfect ray-tracing and an inadequate 1-D reference velocity model. In practice all of these contribute further errors. Thus the tomographic filter is probably poorer than displayed. A more complete filter could be obtained, if starting from the synthetic residuals we produced a 1-D reference model [*Kennett & Engdahl*, 1991], followed by relocation using multiple phases [*Engdahl et al.*, 1998]. We also ignore crustal effects, which could be estimated from *a priori* seismic models [*Ricard et al.*, 1999]. We must add that long period seismic models [*Masters et al.*, 1996] provide a better sampling of some regions that are not well covered in our inversion, but this effect requires further investigation.

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Hans-Peter Bunge, Department of Geosciences, Princeton University, Princeton, N.J. 08544, USA (email: bunge@princeton.edu)

J. Huw Davies, Department of Earth Sciences, University of Liverpool, Liverpool, L69 3GP, UK (e-mail: davies@liverpool.ac.uk)

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